

The study of magnetic reconnection in solar spicules

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Abstract

This work is devoted to study the magnetic reconnection instability under solar spicule conditions. Numerical study of the resistive tearing instability in a current sheet is presented by considering the magnetohydrodynamic (MHD) framework. To investigate the effect of this instability in a stratified atmosphere of solar spicules, we solve linear and non-ideal MHD equations in the $x - z$ plane. In the linear analysis it is assumed that resistivity is only important within the current sheet, and the exponential growth of energies takes place faster as plasma resistivity increases. We are interested to see the occurrence of magnetic reconnection during the lifetime of a typical solar spicule.

Keywords Sun: spicules · magnetic reconnection

1 Introduction

The mechanism of coronal heating is one of the major problems in solar physics. The magnetic structure of the corona can play an important role on the problem of heating, so it should be necessary to study the converting of the magnetic energy to heat.

Magnetic reconnection plays a critical role in many astrophysical processes, e.g. particle acceleration and solar flares. Magnetic reconnection is a topological change in the field which violates the frozen-flux condition of ideal magnetohydrodynamics (MHD). If a magnetic field can leak across the plasma it can reach a lower energy state, in the case of a current sheet, it can undergo

”tearing” into magnetic islands. Tearing instability is responsible for many cases of magnetic field line reconnection process which converts magnetic energy into the thermal and kinetic energy of plasma flows in astrophysical and laboratory plasmas (Priest & Forbes 2000; Birn & Priest 2007; Zweibel & Yamada 2009). Nowadays emphasis in the tearing mode instability is focused on physical effects that result in a much faster rate of field line reconnection.

Yokoyama & Shibata (1995) modeled X-ray and EUV jets and surges observed with $H\alpha$ in the chromosphere by performing a resistive 2D MHD simulation of the magnetic reconnection occurring in the current sheet between emerging magnetic flux and overlying pre-existing coronal magnetic fields. *Hinode* observation revealed that jets are ubiquitous in the chromosphere (Kosugi et al. 2007). De Pontieu et al. (2007), from *Hinode* data estimated the energy flux carried by transversal oscillations generated by spicules. They indicated that the calculated energy flux is enough to heat the quiet corona. He et al. (2009) based on *Hinode/SOT* observations found the signatures of small scale reconnection in spicules. They concluded that magnetic reconnection can exit kink waves along spicules.

Sweet (1958); Parker (1963); Petschek (1964); Soward & Priest (1982) introduced magnetic reconnection as the central process allowing for efficient magnetic to kinetic energy conversion in solar flares and for interaction between the magnetized interplanetary medium and magnetosphere of Earth.

Takeuchi & Shibata (2001) have investigated photospheric magnetic reconnection induced by convective intensification of solar surface magnetic fields, performing 2.5-dimensional MHD numerical simulations. They concluded that in models of solar spicules, upward propagating slow waves or Alfvén waves are usually assumed as initial perturbations. The wave energies due to the

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reconnections are comparable to those assumed in the spicule models. The photospheric magnetic reconnection might be one of the important causes of solar spicules.

Spicules, thin and elongated structures are one of the most pronounced features of the chromosphere. They are seen in spectral lines at the solar limb at speeds of about $20 - 25 \text{ km s}^{-1}$ propagating from the photosphere into the magnetized low atmosphere of the sun (Zaqarashvili & Erdélyi 2009). Their diameter and length varies from spicule to spicule having the values from 400 km to 1500 km and from 5000 km to 9000 km, respectively. Their typical lifetime is 5 – 15 min, however some spicules may live for longer or shorter periods (Murawski & Zaqarashvili 2010). The typical electron density at heights where the spicules are observed is approximately $3.5 \times 10^{16} - 2 \times 10^{17} \text{ m}^{-3}$, and their temperatures are estimated as 5000 – 8000 K (Beckers 1968; Sterling 2000).

In this paper we present numerical simulation of magnetic reconnection due to the tearing mode instability. Section 2 gives the basic equations and theoretical model. In section 3 numerical results are presented and discussed, and a brief summary is followed in section 4.

2 Theoretical modeling

2.1 Equilibrium

The formal description of reconnection requires the choice of a dynamical model. We confine the discussion to magnetohydrodynamics for a finite resistivity (resistive MHD). The corresponding basic equations for the non-ideal MHD in the plasma dynamics are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + \rho \mathbf{g} + \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B} \quad (2)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \quad (3)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (4)$$

$$p = \frac{\rho R T}{\mu}. \quad (5)$$

where ρ is mass density, \mathbf{v} is flow velocity, \mathbf{B} is the magnetic field, p is the gas pressure, R is the universal gas constant, η is constant resistivity coefficient, μ_0

is the vacuum permeability, μ is the mean molecular weight. We assume that spicules are highly dynamic with speeds that are significant fractions of the Alfvén speed ($V_{A0} = B_0 / \sqrt{\mu_0 \rho_0}$).

A planar slab of a uniform plasma is embedded in a sheared force-free magnetic field and surrounded by two perfectly conducting boundaries at $x = 0, L_x$, where L_x is the box size in the x direction:

$$\mathbf{B}_0 = B_{0y}(x) \hat{j} + B_{0z}(x) \hat{k} \quad (6)$$

with

$$\begin{aligned} B_{0y}(x) &= 0, \\ B_{0z}(x) &= \tanh\left(\frac{x - z_t}{z_w}\right) \end{aligned} \quad (7)$$

where $z_t = L_x/2$ is the position of the middle of a spicule and z_w is the thickness of the initial current sheet (the shear length of magnetic field configuration). Since the equilibrium magnetic field is force-free, the pressure gradient is balanced by the gravity force, which is assumed to be $\mathbf{g} = -g \hat{k}$ via this equation:

$$-\nabla p_0(z) + \rho_0(z) \mathbf{g} = 0. \quad (8)$$

2.2 Perturbations

The governing equations defining temporal evolution of perturbations is a set of single-fluid MHD equations:

$$\frac{\partial \psi}{\partial t} = [\phi, \psi] + \eta \nabla^2 \psi, \quad (9)$$

$$\frac{\partial \nabla^2 \phi}{\partial t} = [\nabla^2 \psi, \psi] \quad (10)$$

where ψ , the magnetic flux and ϕ , the stream function are defined as follows:

$$\mathbf{B}(x, z, t) = \nabla \psi(x, z, t) \times \hat{j} + b(x, z, t) \hat{j}, \quad (11)$$

$$\mathbf{V}(x, z, t) = \nabla \phi(x, z, t) \times \hat{j} + v_y(x, z, t) \hat{j}. \quad (12)$$

The Poisson bracket notation $[A, B] = (\nabla A \times \nabla B) \cdot \hat{k}$ is adopted in Eqs. 9 and 10. Thus, the linearized dimensionless MHD equations in terms of ψ and ϕ are given by:

$$\frac{\partial \psi}{\partial t} = \frac{\partial \phi}{\partial z} \frac{\partial \psi_0}{\partial x} - \eta \nabla^2 \psi \quad (13)$$

$$\frac{\partial \nabla^2 \phi}{\partial t} = \frac{\partial \nabla^2 \psi}{\partial z} \frac{\partial \psi_0}{\partial x} - \frac{\partial \psi}{\partial z} \frac{\partial \nabla^2 \psi_0}{\partial x} \quad (14)$$

where the partial differences are obtained from Eqs. 11 and 12 as follows:

$$\frac{\partial \phi}{\partial z} = -v_x, \quad \frac{\partial \psi_0}{\partial x} = B_{0z}, \quad j_{0y} = \nabla^2 \psi_0.$$

Here, velocity, magnetic field, magnetic flux, stream function, time and space coordinates are normalized to V_{A0} , B_0 , $B_0 a$, a^2/τ_A , τ_A , and a (spicule radius), respectively. The equilibrium profiles are shown in Figure 1.

3 Numerical results and discussion

We use the finite difference and the Fourth-Order Runge-Kutta methods to take the space and time derivatives in the coupled Eqs. 13 and 14. The implemented numerical scheme is using by the forward finite difference method to take the first spatial derivatives with the truncation error of (Δx) , which is the spatial resolution in the x direction. The order of approximation for the second spatial derivative in the finite difference method is $O((\Delta x)^2)$. On the other hand, the Fourth-order Runge-Kutta method takes the time derivatives in the questions. The computational output data are given in 17 decimal digits of accuracy.

We set the number of mesh-grid points as 256×256 . In addition, the time step is chosen as 0.001, and the system length in the x and z dimensions (simulation box sizes) are set to be $(0, \pi)$ and $(0, 2\pi)$.

The parameters in spicule environment are as follows: $a = 200$ km (spicule radius), $L = 6000$ km (Spicule length), $v_0 = 25$ km s $^{-1}$, $n_e = 11.5 \times 10^{16}$ m $^{-3}$, $B_0 = 1.2 \times 10^{-3}$ Tesla, $T_0 = 14\,000$ K, $g = 272$ m s $^{-2}$, $R = 8300$ m 2 s $^{-1}$ k $^{-1}$ (universal gas constant), $V_{A0} = 77$ km/s, $\mu = 0.6$, $\tau = 2.5$ s, $\rho_0 = 1.9 \times 10^{-10}$ kg m $^{-3}$, $p_0 = 3.7 \times 10^{-2}$ N m $^{-2}$, $\mu_0 = 4\pi \times 10^{-7}$ Tesla m A $^{-1}$, $z_w = 0.5$ and $z_t = 1.57$ (in our dimensionless units), $H = 400$ km, $\eta = 10^3$ m 2 s $^{-1}$, and $k = 2\pi/L_z = 1$ (dimensionless wavenumber normalized to a).

Figure 2 shows the contour plots of the perturbed flux function at different times, $t = 0$ s, $t = 150$ s, $t = 300$ s and $t = 450$ s. As tearing instability proceeds, magnetic islands continuously emerge and develop as a result of ongoing magnetic field line reconnection in the considered lifetime of a solar spicule. In this figure, the formation of magnetic islands characterized by the magnetic X and O points can be seen clearly there. The growth rate of tearing mode instability can be numerically obtained through calculating the slope of energy-time graph at linear stage.

Figure 3 shows temporal variations of the magnetic reconnection rate. The reconnection rate is obtained

by certifying the magnetic reconnection site at each time step, which is found from the value of the magnetic flux at the point (128, 163) (the reconnection cite in the simulation box). In this figure, the reconnection rate increases exponentially during a spicule life time which is due to the linear phase of the instability (Yokoyama & Shibata 1996). The gas density decreases at neutral point because of gravitational downflow and of plasma rarefaction due to outflows accelerated by the magnetic tension of the reconnected field lines when island is formed. Our simulations show that the reconnection can be occurred during of a spicule life time. It is demonstrated by He et al. (2009) observationally in a typical limb spicule.

The logarithmic energy-time graph which has been shown in Figure 4, display the time variation of dimensionless magnetic energy, $E_m = \int (B_x^2 + B_z^2) dv$ and kinetic energy, $E_k = \int (v_x^2 + v_z^2) dv$. In the linear phase, the logarithmic magnetic and kinetic energies grow linearly (or exponentially in the non-logarithmic case) with time.

4 Conclusion

The linear dynamics of magnetic reconnection in the spicule structure was studied numerically. A set of incompressible magnetohydrodynamic (MHD) equations described the evolution of tearing instability of a slab of uniform plasma which had been embedded in a force-free equilibrium magnetic field. The resistivity of plasma was the main agent to trigger the reconnection process by breaking of the frozen-in field constraint. The considered plasma medium in this study was the solar spicule environment. In fact, the ongoing reconnection process is intrinsically associated with the formation of magnetic islands, and in the linear phase of instability, the magnetic and kinetic energies in logarithmic scale grow linearly as it is expected.

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References

- Beckers, J.M.: Sol. Phys. **3**, 367 (1968)
- Birn, J., Priest, E.R.: Reconnection of magnetic fields: MHD and collisionless theory and observations. Cambridge Uni. Press (2007)
- De Pontieu, B., McIntosh, S.W., Carlsson, M., et al.: Science **318**, 1574 (2007)
- He, J., Marsch, E., Tu, Ch., Tian, H.: Astrophys. J. **705**, 217 (2009)

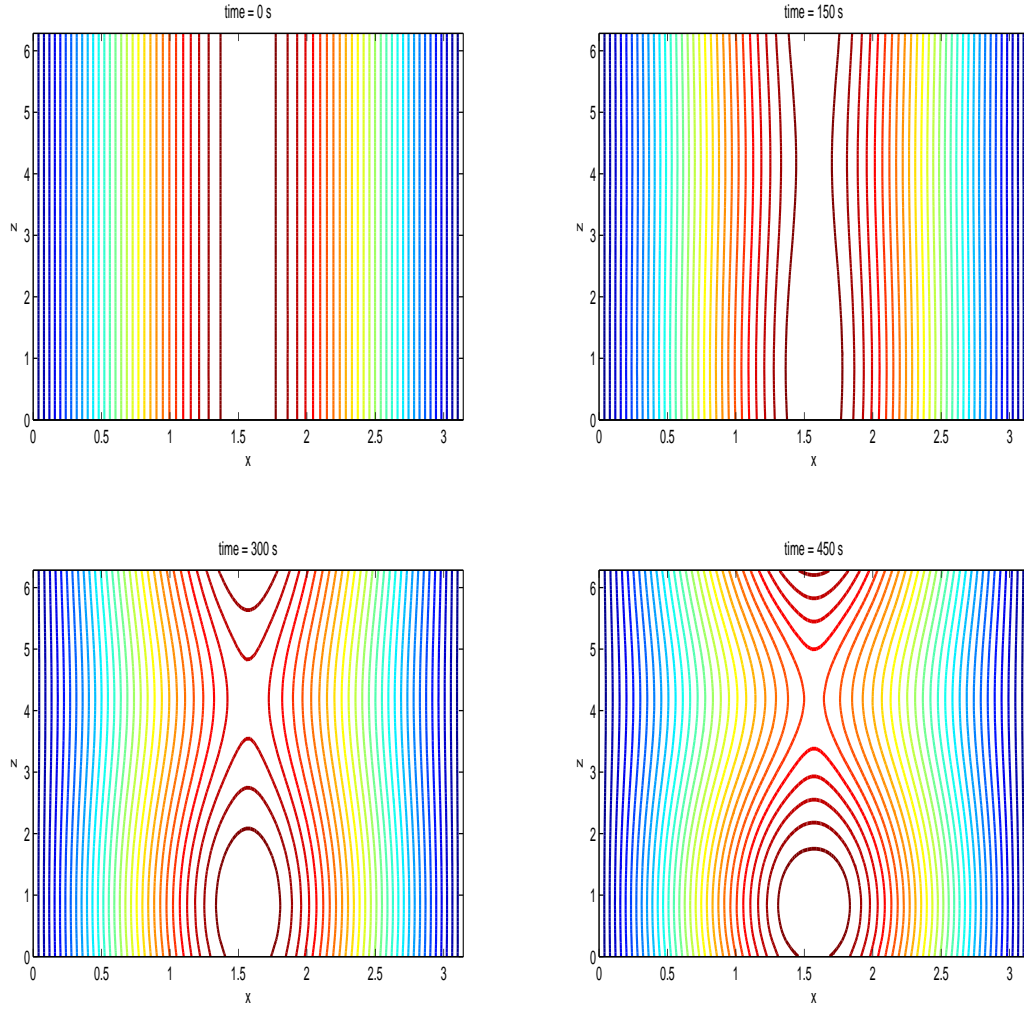


Fig. 2 Contour plots of perturbed magnetic flux function at different times.

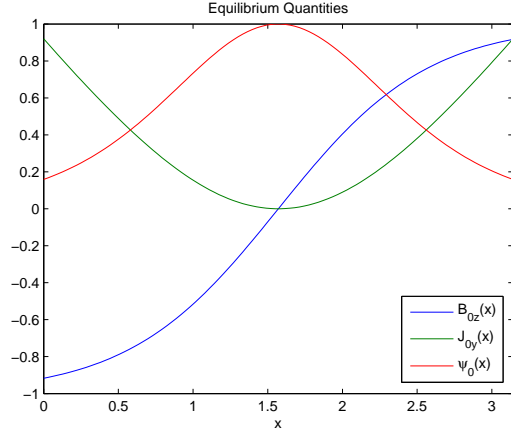


Fig. 1 The equilibrium profiles of magnetic field, B_{0z} , current density, J_{0y} and flux function ψ_0 .

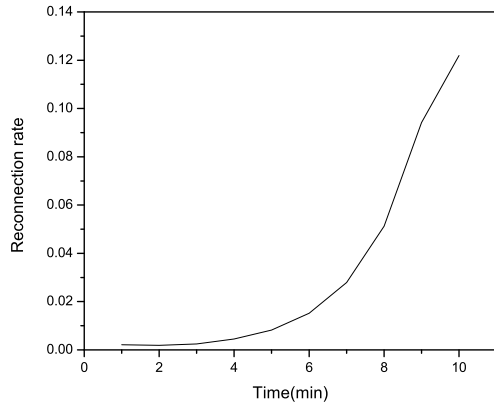


Fig. 3 Time evolution of the magnetic reconnection rate.

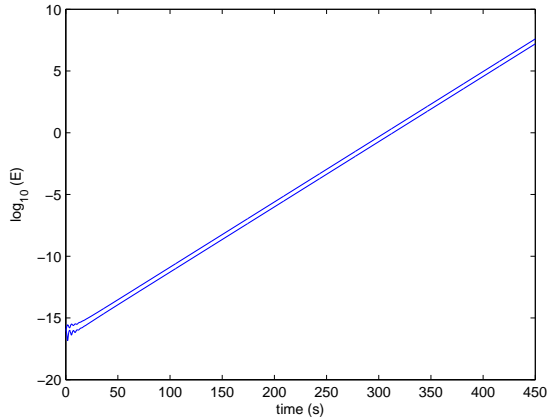


Fig. 4 Time evolution of magnetic and kinetic energies in the linear phase of the reconnection.

- Kosugi, T. et al.: *Sol. Phys.* **243**, 3 (2007)
- Murawski, K., Zaqarashvili, T.V.: *Astron. Astrophys.* **519**, A8 (2010)
- Petschek, H.E.: in *Proc. AAS-NASA Symp. on Physics of Solar Flares*, ed. W.N. Hess (NASA SP-50), 425 (1964)
- Parker, E.N.: *Astrophys. J. Suppl. Ser.* **8**, 177 (1963)
- Priest, E.R., Forbes, T.: *Magnetic reconnection: MHD theory and applications*. Cambridge Uni. Press (2000)
- Soward, A.M., Priest, E.R.: 1982, *J. Plasma Phys.*, **28**, 335 (1982)
- Sweet, P.A.: 1958, in *IAU Symp. 6, Electromagnetic Phenomena in Cosmical Phys.*, ed. Lehnert, B. (Cambridge Uni. Press) 123 (1958)
- Sterling, A.C. 2000, *Sol. Phys.* **196**, 79 (2000)
- Takeuchi, A., Shibata, K.: 2001, *Astrophys. J.* **546**, L73 (2001)
- Yokoyama, T., Shibata, K.: *Nature* **375**, 42 (1995)
- Yokoyama, T., Shibata, K.: *Publ. Astron. Soc. Japon* **48**, 353 (1996)
- Zaqarashvili, T.V., Erdélyi, R.: *Space Sci. Rev.* **149**, 335 (2009)
- Zweibel, E.G., Yamada, M.: *Ann. Rev. Astron. Astrophys.*, **47**, 291 (2009)